Chapter 9
Example: Chester Creek Flood-Damage-Reduction Plan Evaluation

9-1. Overview

This section provides a detailed example of the flood-damage plan evaluation procedures described in this document. It illustrates evaluation of economic efficiency and engineering performance accounting for uncertainty, using as an example the metropolitan Chester Creek, PA, basin. Floods have caused significant damage in this basin. The U.S. Army Engineer District, Philadelphia, addressed flooding problems in the basin in a water resources study completed in September 1978 (USACE 1977, 1978a, 1978b); data used herein are adapted from that study, with modifications and expansions to illustrate critical concepts.

9-2. Description of Problem

a. Setting. Chester Creek originates near West Chester, PA, and flows southeasterly for approximately 40 km to a confluence with the Delaware River at Chester, PA, as shown in Figure 9-1. Various tributaries intersect the Chester Creek main stem; the largest of these are the East Branch and West Branch. The 176.1-km^2 drainage basin is located within the Philadelphia Standard Metropolitan Statistical Area. Flow in Chester Creek is measured at a U.S. Geological Survey (USGS) gauge near

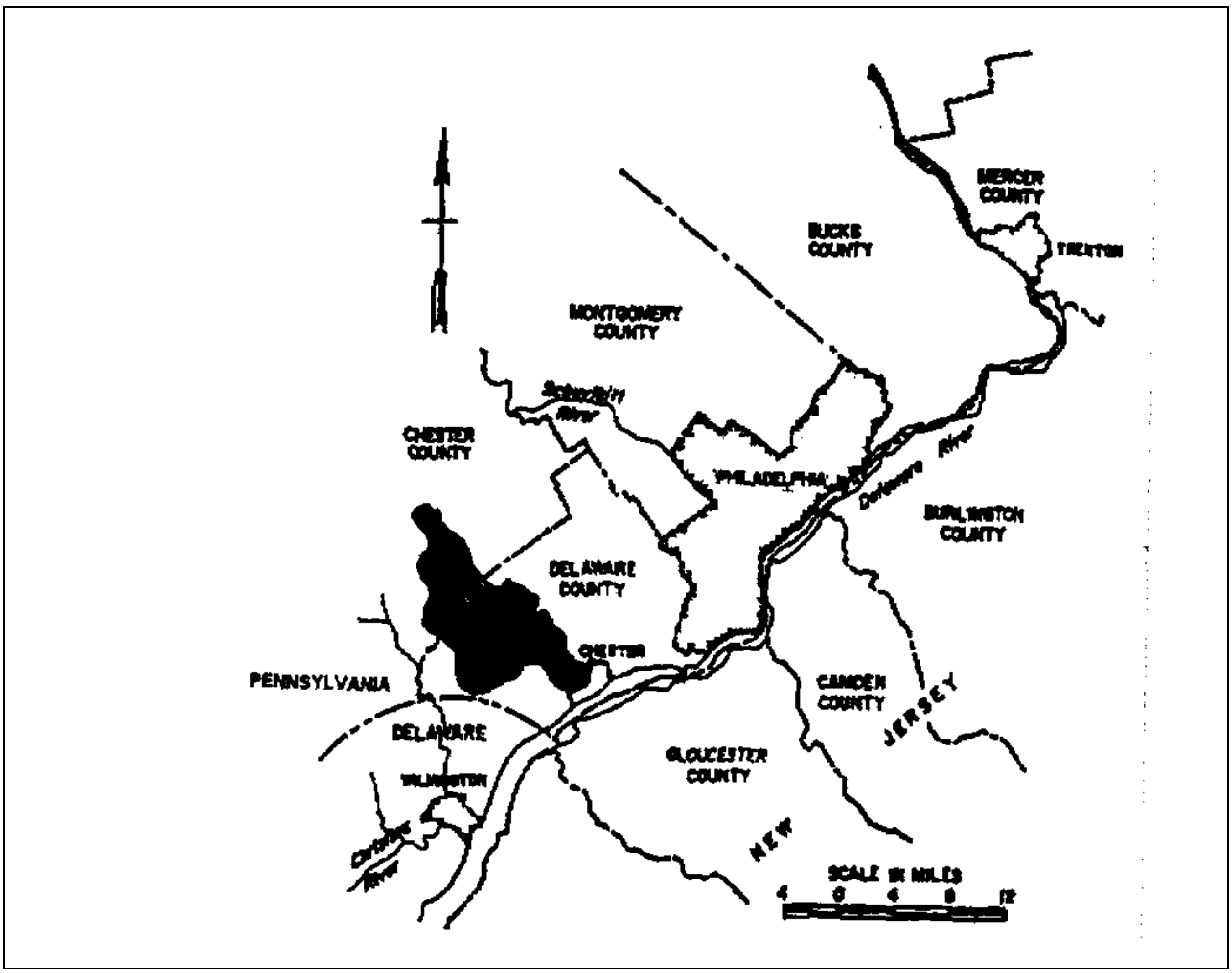

Figure 9-1. Chester Creek location map

Dutton Mill Road in Brookhaven, PA. The drainage area upstream of the gauge is 158.2 km^2, approximately 90 percent of the total basin area. The basin includes 21 municipalities, with an estimated 1990 population of 10,5400 within the basin boundary (USACE 1978b).

b. Flooding History. Developed communities in the basin have been flooded periodically, primarily due to high-intensity summer and fall thunderstorms falling on the relatively long, narrow, steep basin. The worst flooding occurs in the lower main stem reaches. Flooding there is aggravated by many channel constrictions and encroachments. Increased development in the upper portion of the basin promises to worsen the flood problem, as urbanization increases the volume and peak discharge. Table 9-1 shows the largest flood events recorded at the USGS gauge and estimates of the corresponding damage in the Chester Creek basin. The flood of record, in September 1971, was 594.7 m^3/s. This event inundated 130 businesses and 732 residences. Second-story flooding was common, and eight lives were lost.

Table 9-1
Historical Floods in the Chester Creek Basin (from USACE (1978a,b))

Date	Discharge at Dutton Mill Gauge, in m^3/s	Estimated Damage, in Millions of 1978 Dollars
13 Sep 1971	594.7	17.6
25 Nov 1950	407.8	4.6
12-13 Sep 1960	281.5	1.6
28 Jul 1969	270.7	1.4
18-19 Aug 1955	265.6	1.3
23-24 Aug 1933	177.0	0.5
22-23 Jun 1972	175.0	0.5
23 Jul 1938	145.0	0.2
09-10 Jan 1936	141.6	0.2
03 Aug 1950	141.6	0.2
15 Mar 1967	135.1	0.1
07 Mar 1967	133.6	0.1
01 Aug 1945	125.7	0.1

c. Previous studies. As noted, the Philadelphia District addressed flooding problems in the basin in a 1978 water resources study. Pennsylvania's State Water Plan presented an investigation of flooding problems and damage-reduction plans throughout the region. The Delaware Valley Regional Planning Commission developed drainage plans for southeastern Pennsylvania and reported these in the *1973 Drainage and Flood Control Work Program*.

9-3. Study Plan

a. The proper approach to finding a solution to the Chester Creek flood-damage problem is as follows: (1) analyze the flood problem to identify opportunities for damage reduction; (2) formulate a set of damage-reduction alternatives; (3) evaluate each alternative in terms of economic and engineering performance, accounting for the uncertainty in this evaluation, (4) display the results so that alternatives can be compared; and (5) identify and recommend a superior plan from amongst the alternatives.

b. For the example herein, a single damage reach is used for the formulation and evaluation, with all damage related to stage at the USGS stream gauge. Subbasins are defined as necessary to permit derivation of future and with-project discharge-exceedance probability relationships via application of catchment-runoff process models.

9-4. Present, Without-Project Condition

a. The standard for damage-reduction benefit computation and for engineering performance evaluation in Chester Creek is the without-project condition. Expected annual damage, annual exceedance probability, long-term risk, and conditional non-exceedance probability are computed for this standard for present and for future conditions. For the computation, discharge-frequency, stage-discharge, and stage-damage relationships were developed following standard Corps procedures described herein and in other pertinent documents. In each case, the characteristics of uncertainty in the relationships are described in terms of statistical models of errors.

b. The present, without-project condition for Chester Creek includes a variety of levee and floodwall projects that have been constructed in the basin to provide some relief from the flooding. Local governments built the Crozer Park Gardens, Crozer Park, and Toby Farms levees, and the Commonwealth of Pennsylvania has improved local drainage facilities, thereby reducing local flooding for frequent events. The Eyre Park levee project was constructed by the Corps and turned over to the City of Chester in June 1954. [The peak water-surface elevation during the 1971 flood exceeded the levee height by 2 to 3 m, causing a levee breach. For the example herein, however, this levee is assumed to be functional. The protection afforded is accounted for in computation of present, without-project expected annual damage and annual exceedance probability.]

(1) *Discharge-probability function*. The existing, without-project discharge-frequency relationship was developed from the sample of historical annual maximum discharge observed at the Dutton Mill gauge. The equivalent of 65 years of data are available. This is a random, unregulated, homogenous series of flow data which can be evaluated using the procedures outlined in EM 1110-2-1415 and Bulletin 17B (Interagency Advisory Committee 1982). Accordingly, a log-Pearson type III statistical model was fitted to the data, using the computer program HEC-FFA (USACE 1992a) to define the median exceedance probability function. The parameters of the present, without-project Chester Creek discharge-probability function are: mean of logs of annual maximum discharge = 1.959; standard deviation of logs = 0.295; and adopted skew of log = 0.4. With these parameters, the function shown in Table 9-2 was computed. Note that this is the median function; the expected-probability adjustment was not used, as this adjustment would duplicate the accounting for uncertainty that is accomplished with sampling procedures.

Table 9-2
Chester Creek Present, Without-Project Discharge-Probability Relationship

Probability of Exceedance	Discharge, in m^3/s
0.002	898.8
0.005	676.1
0.01	538.5
0.02	423.0
0.05	298.8
0.10	222.5
0.20	158.4
0.50	87.0
0.80	50.9
0.90	39.4
0.95	32.3
0.99	22.9

(2) *Uncertainty of discharge-exceedance probability function*. From a hydrologic engineering perspective, the sample at the Dutton Mill gauge is large, but from a statistical-analysis perspective, it is not. With a sample size of only 65 years, errors in the mean and standard deviation of the logarithms can lead to considerable errors in fitting the relationship, and hence in predicting quantiles. As recommended in Bulletin 17B, these errors were described with a non-central *t* probability model. Figure 9-2 illustrates the results: it is a probability relationship for the 0.01 event. The figure shows that, based on fitting the annual maximum discharge-probability function with 65 years of data at Dutton Mill, the probability is 0.05 that the true annual exceedance probability = 0.01 discharge is 413.5 m^3/s or less; it is 0.5 that the true discharge is 538.5 m^3/s or less; and it is 0.95 that the true value is 753.3 m^3/s or less. Similar relationships can be developed for any selected annual exceedance probability.

Another common interpretation of this description of uncertainty is that the probability is 0.90 (=0.95-0.05) that the true 0.01 probability discharge is between 413.5 m^3/s and 753.3 m^3/s. In that case, 413.5 m^3/s and 753.3 m^3/s are the so-called 90-percent confidence limits. These limits, along with the median probability function, are plotted in Figure 9-3. Note that the confidence limits are centered about the median estimate of the quantile: The probability is 0.50 that the true 0.01 probability discharge is greater than or less than the value predicted with the log Pearson type III parameters estimated with the sample.

(3) *Stage-discharge function.* The present, without-project stage-damage relationship at the Chester Creek index point was developed from water-surface profiles computed with computer program HEC-2 (USACE 1991) as follows:

(a) Field surveys were carried out to acquire the necessary geometric data; elevations were reported to the nearest foot (0.3 m), and distances were determined with stadia rod readings.

(b) Manning's *n* values were estimated by calibration, using high-water marks from the September 1971 flood; this event was approximately a 0.01 exceedance probability event, judging from values shown in Tables 9-1 and 9-2.

(c) Once calibrated, the HEC-2 model was exercised for a range of discharge values to compute the stage at the index location. The results are summarized in Table 9-3. Note that the computed relationship predicts stage for discharge values much greater than ever observed. This is necessary for proper evaluation of damage due to rare events.

(4) *Uncertainty of stage-discharge function.* The stage-discharge relationship is not known with certainty, due to uncertainty in estimating the *n* values, in defining

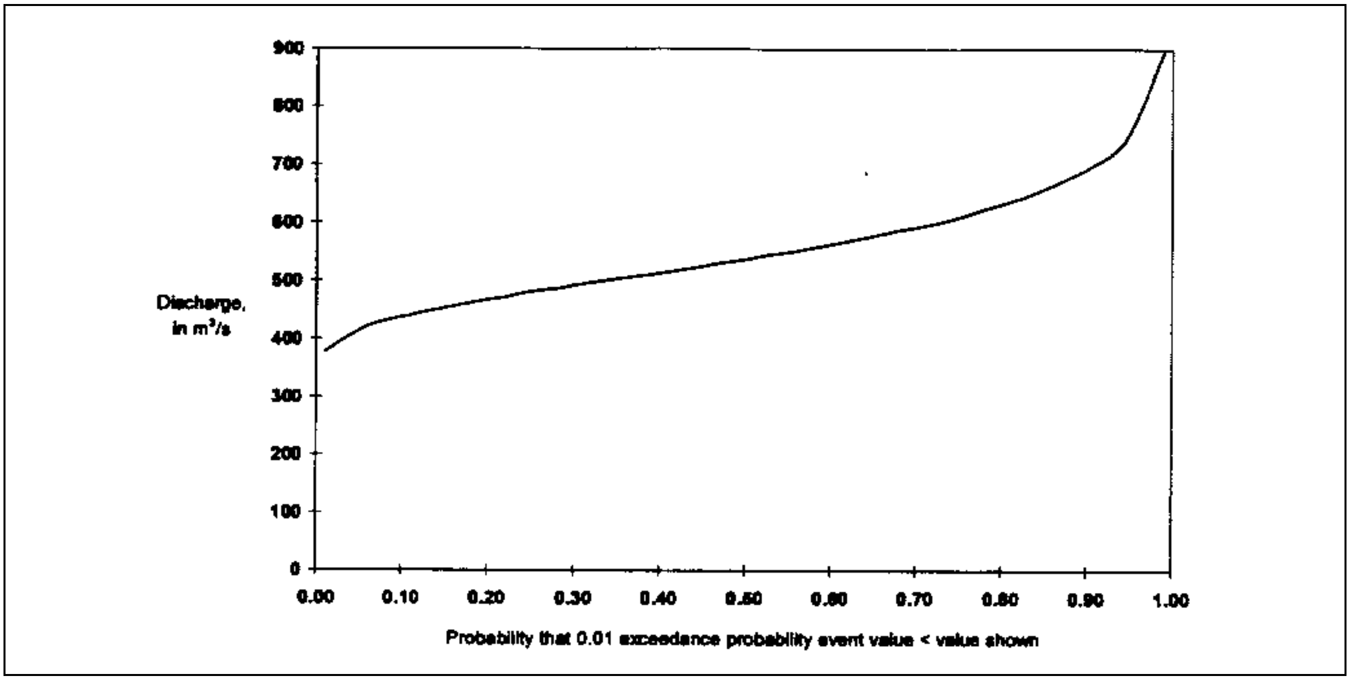

Figure 9-2. Description of uncertainty in .01 exceedance probability discharge estimate

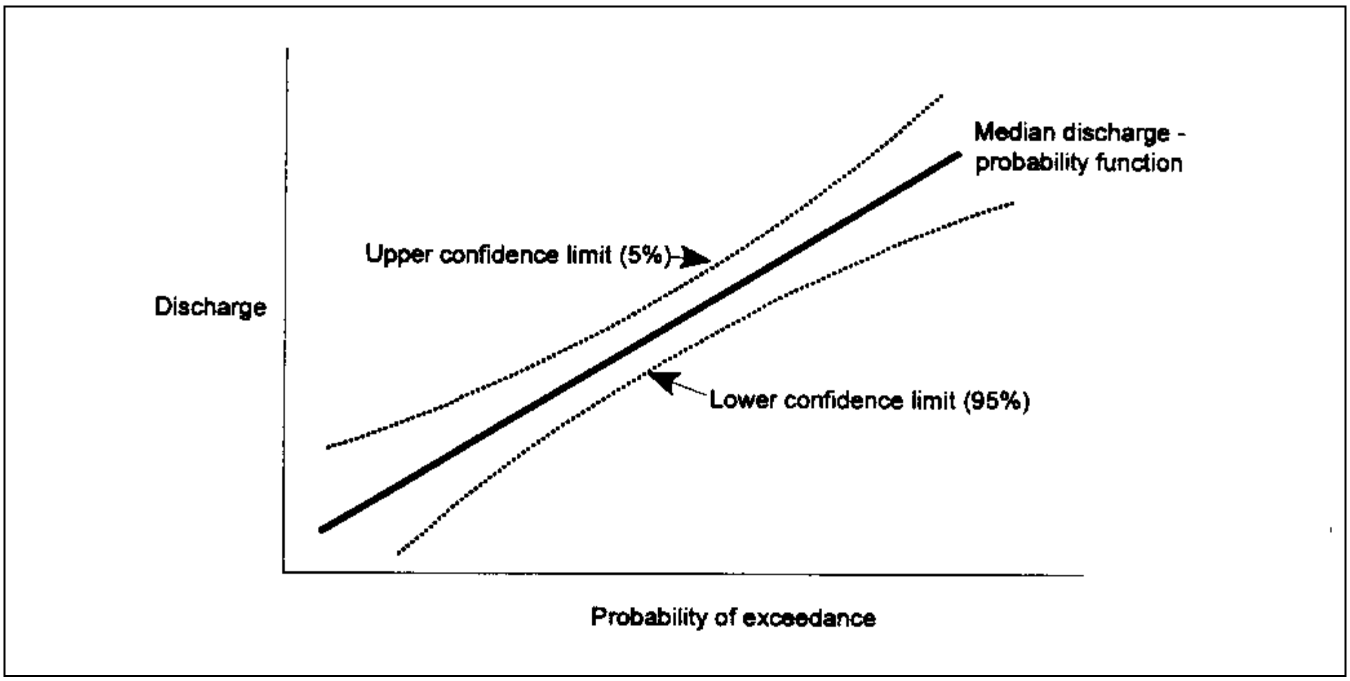

Figure 9-3. Chester Creek discharge-probability function

Table 9-3
Chester Creek Present, Without-Project Stage-Discharge Relationship

Stage, in m	Discharge, in m^3/s
1.97	084.4
2.39	100.4
3.39	168.2
4.07	228.4
4.58	277.5
5.50	383.7
6.70	538.5
7.13	605.8
7.47	651.5
7.75	721.7
8.10	838.2
8.79	1030.8
8.99	1159.1
9.57	1297.1

the exact cross-section geometry, in measuring distances, in estimating losses at expansions and contractions, etc. For Chester Creek, the relationship uncertainty is quantified following the procedure developed by HEC (USACE 1986), which is described in Chapter 5 of this document. This suggests that errors in predicting stage for a given discharge are normally distributed with mean equal zero and standard deviation related to the manner in which the stage-discharge relationship is established. For Chester Creek, the standard deviation for the 0.01 probability discharge was estimated to equal 0.3 m, as follows:

(a) The HEC-2 model calibration was reviewed. About two thirds of the computed elevations fell within ± 0.3 m of the observed high-water marks. In a normal distribution, approximately 63 perent of observations should fall within plus or minus one standard deviation, so it could be inferred that the standard deviation of error in stage is about 0.3 m.

(b) Based on comparison with the USGS rating, the estimated *n* values are graded "good." Guidance in Chapter 5 suggests that for good estimates of *n*, with channel geometry based on field surveys, the minimum standard deviation for the 0.01 probability exceedance event is 0.2 m.

(c) Finally, sensitivity of predicted stage to *n* values and other parameters was investigated. The analyses yielded upper and lower bounds on the stage associated with the 0.01 probability exceedance discharge. The difference in these stages averaged 1.2 m. Assuming that the distribution of errors about the best estimate is normal and that 95 percent of the values predicted would fall in this range, leads to the conclusion that four standard deviations encompass 1.2 m. Thus, each standard deviation is about 0.3 m.

The resulting statistical model that describes errors in predicting the stage associated with discharge of 538.5 m^3/s (the median estimate of the 0.01 exceedance probability discharge) is shown in Figure 9-4. For other values of discharge, a similar description is developed, with the standard deviation of error defined as follows:

(a) For discharge values greater than the 0.01 exceedance probability discharge, the standard deviation is assumed equal to the standard deviation for the 0.01 exceedance probability discharge.

(b) For discharge values smaller than the 0.01 exceedance probability discharge, the standard deviation is the standard deviation of error associated with the 0.01 exceedance probability discharge multiplied by the ratio of the given discharge to the 0.01 exceedance probability discharge. This multiplier will always be less than 1.

(5) *Stage-damage function.* The stage-damage relationship for Chester Creek was developed with the following procedure:

(a) All structures in the basin were categorized as either residential, commercial, industrial, or public facilities. Utilities, highways, and agricultural facilities that would be damaged were identified. Residential structures were further categorized as either one-story with no basement, one-story with basement, two-story with no basement, two-story with basement, split level with no basement, split level with basement, or mobile.

(b) Representative structures in each residential category were selected and assessed to define an average-case inundation depth-damage relationship for that category. Properties in other categories were assessed to establish a unique depth-damage relationship for each.

(c) The first-floor elevation of each structure was estimated. In the case of the assessed structures, these elevations were found to the nearest 0.3 m (1 ft), by surveying. For others, the elevation was estimated from maps with contours plotted at 0.6-m (2-ft) intervals.

(d) All inundation depth-damage relationships were converted to stage-damage relationships and aggregated at

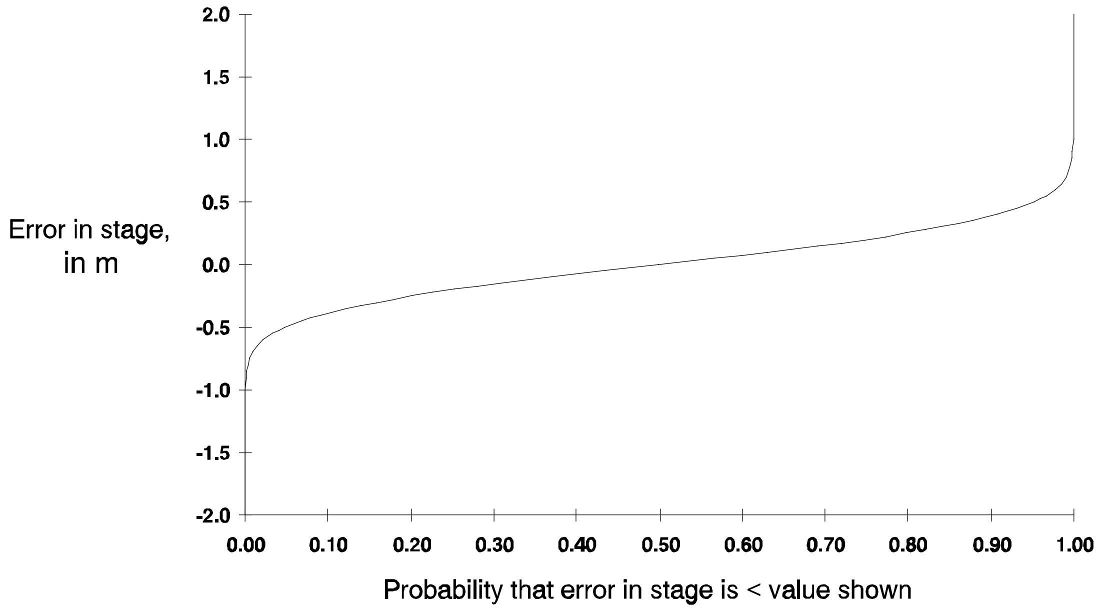

Figure 9-4. Stage uncertainty description for discharge = 538.5 m^3/s

the index point, using a reference flood to relate stage at the index point and stage at the individual structures.

(e) Flood emergency costs were estimated as a function of stage at the index point. These costs were added to the inundation damages to obtain an aggregated relationship.

Table 9-4 shows the aggregated stage-damage function. This function does not account for the existing Eyre Park levee project.

(6) *Stage-damage function uncertainty.* Uncertainty in the stage-damage relationship is due to (a) errors in estimating structure elevations, (b) errors in assessing damage to structures, and (c) errors in assessing damage to contents. To describe this uncertainty in the Chester Creek study, a statistical distribution of error was defined for each of these three components, and the distribution of total error in predicting damage for each stage was developed by sampling. The resulting normal distribution of error has a mean error of zero, and standard deviations are shown in Table 9-4.

Table 9-4
Chester Creek Present, Without-Project Stage-Damage Relationship

Stage, in m	Inundation Damage, in $1000	Standard Deviation of Error in Damage, in $1000
3.35	0.0	0.0
4.27	25.7	13.6
4.57	88.6	28.6
5.18	339.3	55.7
5.49	525.1	77.5
6.10	1,100.0	114.1
6.71	2,150.6	182.9
8.23	5,132.8	333.5
8.53	5,654.2	365.9
9.14	6,416.5	403.6
9.45	6,592.2	410.8

The Eyre Park levee project will reduce damage if it performs as designed. However, that performance is uncertain, as this levee is not a new levee. To account for this, the uncertainty is described with a statistical model that is sampled as the stage-damage function is sampled. For this model, the PNP is estimated by a geotechnical engineer as 5.78 m, and the probability of failure at that stage is 0.15. The PFP is estimated as 6.71 m, and the probability of failure at that stage is 0.85. For stages between the PNP and PFP, a linear relationship is assumed.

(7) *Economic analysis.* Expected annual damage for the present, without-project condition was estimated with annual-event sampling and averaging, accounting explicitly for uncertainty in all relationships. The estimate is $78,100; that is, without any action, over the long term, the average annual flood damage will be $78,100. In most years, the damage will be zero, but occasionally the damage is great, thus increasing the average.

(8) *Engineering performance.* Through annual flood sampling, the annual exceedance probability for the present, without-project condition is estimated as 1.7 percent. That is, the probability that the existing levee will fail is 0.017 percent. The conditional non-exceedance probability of the without-project system for the 0.01 exceedance probability event was estimated also via sampling, accounting for the uncertain performance of the levee. Figure 9-5 is the failure-frequency relationship for the levee for the 0.01 exceedance probability event. By sampling, the expected probability that the 0.01 exceedance probability event will not exceed the PNP is found to be 0.092. That is, there is a 9.2-percent chance that the stage will not exceed the PNP. Similarly, the expected probability that the 0.01 exceedance probability event will not exceed the PFP is 0.503. The probability of no structural failure is 0.85 at the PNP stage and 0.15 at the PFP stage. The expected value is the integral of the shaded area in the figure. In this case, that is 0.298. This is the conditional non-exceedance probability of the levee by the 0.01 exceedance probability event.

9-5. Future, Without-Project Condition

a. Description.

(1) Damage-reduction benefits and engineering performance must be evaluated over the project lifetime and compared to the without-project condition. Consequently, the without-project condition must be described as a function of time if conditions in the basin will change over time. In Chester Creek, as in most basins, development is anticipated. This development will alter the discharge-probability, stage-discharge, and stage-damage relationships. The modified relationships must be used, in turn, to evaluate future flood damage and system performance.

(2) The Chester Creek discharge-frequency relationship is expected to change as a consequence of changes in land use in the basin. The long-term plans for the upper basin anticipate development of urban neighborhoods on land that currently is either open space or is in agricultural use as the population spreads outward from the City of Chester. Such development will increase the volume of runoff, and local drainage improvements that accompany the development will speed the runoff into Chester Creek. While small detention basins planned for the urban areas may provide some relief from the volume increase for smaller, more-frequent events, the overall net impact will be an increase in discharge for any specified probability.

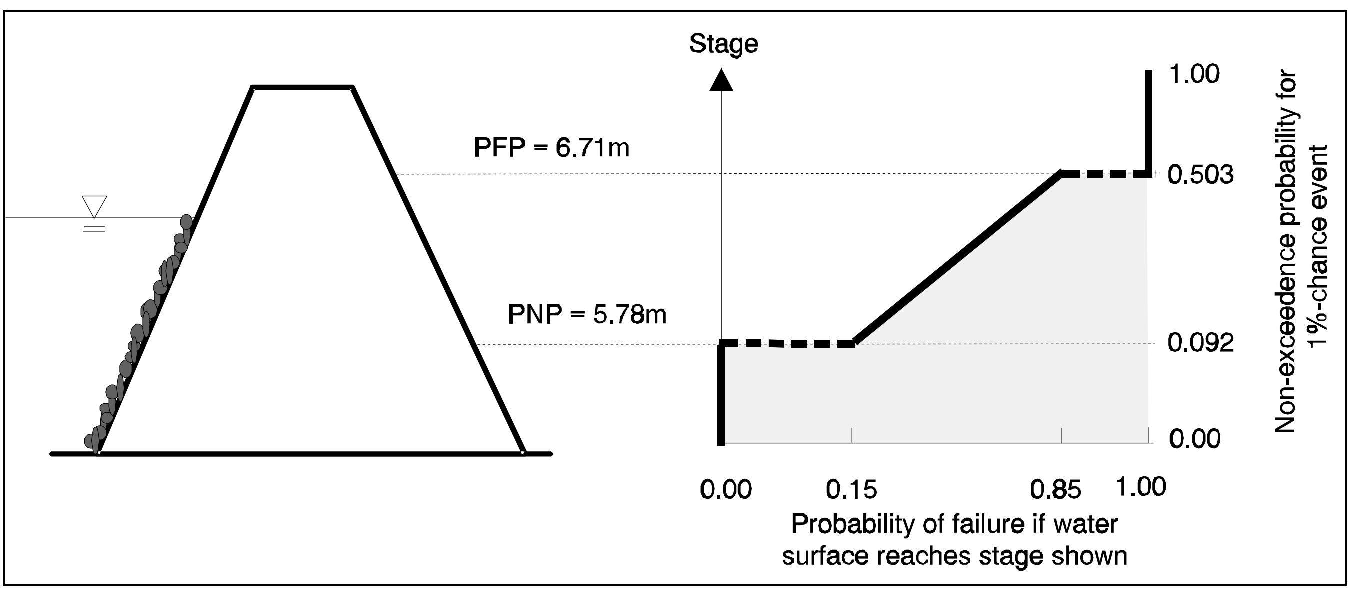

Figure 9-5. Conditional non-exceedance

(3) For economic and engineering performance analysis, a discharge-exceedance probability relationship should be estimated for each year in which significant changes are forecast. These relationships might be estimated with a rainfall-runoff-routing model, using procedures described in EM 1110-2-1417. Discharge-exceedance probability relationships for intermediate years may be estimated by interpolation if the changes are gradual.

(4) The Chester Creek stage-discharge relationship is expected to change over time as the channel is modified. Several communities have expressed a desire to bridge the channel to provide access to new development. The bridges are planned so that the low chord of each is above the current best estimate of the 0.01 exceedance probability stage. However, for larger events, the bridges will obstruct the flow, and thus may increase the stage for a given discharge. Further, a portion of the floodplain has been designated a riparian habitat, so channel maintenance will be restricted. This, in turn, will increase the roughness, impede flow, and lead to increases in stage.

(5) A stage-discharge relationship should be estimated for each year in which significant changes to the channel are forecast. These relationships might be estimated with a river hydraulics model, using procedures described in EM 1110-2-1416. Stage-discharge relationships for intermediate years may be estimated by interpolation if the changes are gradual.

(6) Increased development within the basin might be expected to lead to increases in damage. However, in the Chester Creek basin, all communities participate in the federal flood insurance program. These communities have ordinances that will limit any new construction within the 0.01 exceedance porbability floodplain. This will limit any increase in damage, even with the new development, and may, in fact, reduce damage as low-lying properties reach the end of their utility and are abandoned or razed. Furthermore, the Chester Redevelopment Authority intends to redevelop the Eyre Park area by purchasing and demolishing 216 homes there. This will lead to a decrease in damage for a given stage.

(7) As with the other relationships, a stage-damage relationship should be defined for each year in which significant changes occur, and relationships should be interpolated for intermediate years if the changes are gradual.

b. Economic and engineering performance. The same procedures used for evaluation of present, without-project expected annual damage and other indices are used to evaluate future, without-project economic and engineering performance. To account for uncertainty in the future-condition functions, the error distributions must be defined. In certain cases, estimating the form of these distributions may be easier for future conditions than for present. For example, in Chester Creek, a channel modification plan is authorized for a short reach of the main stem. Local authorities will remove a low bridge and modify the channel to yield a rock-lined trapezoidal cross section in the reach adjacent to the bridge location. In that case, the channel geometry, roughness value, and losses will be known reasonably well. Thus, the future condition standard deviation in stage prediction, in that reach, will be less than the 0.3 m used for the existing condition. Likewise, with structures removed from the floodplain, the likelihood of error in enumerating structures for the stage-damage relationship is reduced. On the other hand, the discharge-probability relationship is more uncertain. For the present, without-project condition, this relationship was developed via statistical analysis of the equivalent of 65 years of observed data. For the future condition, a rainfall-runoff-routing model must be used with handbook loss-model and unit hydrograph parameters to estimate the incremental runoff from portions of the catchment in which land use changes. The result may be a frequency curve that is approximately equivalent, in terms of uncertainty, to one based on statistical analysis of say 50 years of data. If that were the case, the error in predicting discharge for a specified event will increase.

9-6. Proposed Damage-Reduction Plans

a. The Chester Creek study team identified an initial set of 47 damage-reduction alternatives (USACE 1977). This set included various sizes of, locations for, and combinations of measures shown in Table 9-5.

b. Seventeen of the plans address flooding problems in the entire basin, 20 address flooding in Chester, and the remainder focused on flood-damage reduction in specific communities in the basin. The initial set of alternatives was screened to eliminate obviously inferior alternatives. Using economic criteria only, plans that could not meet the national objective were eliminated. To account implicitly for the uncertainty of this early screening, plans on the margin were retained. This screening yielded the smaller set of alternatives shown in Table 9-6. These are considered in more detail herein.

9-7. Levee Plans

a. General. The four levee alternatives entail construction of new levees that meet all Corps structural

Table 9-5
Measures in Initial Set of Chester Creek Alternatives

- Bridge modifications and replacements
- Bypass channels
- Channel modifications, including deepening, widening, realignment
- Dry detention reservoirs
- Levees and floodwalls
- Natural channel storage (natural impoundments)
- Multipurpose reservoirs
- Contingency floodproofing
- Flood insurance
- Regulatory measures, including floodplain zoning and floodway ordinances
- Flood warning and preparedness planning
- Land development regulations
- Permanent evacuation or relocation
- Pervious paving
- Temporary evacuation

Table 9-6
Flood-Reduction Alternatives for Chester Creek

- Levee alternatives: construct levees along the main stem. The following alternative heights are proposed: 6.68 m, 7.32 m, 7.77 m, 8.23 m.
- Channel-modification plan: straighten and enlarge the main stem in the vicinity of the City of Chester, increasing capacity from 170 m^3/s to approximately 255 m^3/s.
- Detention-storage plan: construct a dry, 5.55×10^6-m^3 detention reservoir on the West Branch, at approximately the confluence with the main stem. Contributing area of the reservoir is 57.8 km^2.
- Mixed-measures plan. Straighten and enlarge the channel as above and construct the 5.55×10^6-m^3 detention reservoir.

and geotechnical stability criteria. Thus for the proposed levees, the PNP and PFP correspond to the elevation of the top of the levee. The levees are located along Chester Creek in the lower portion of the basin and provide protection for the urbanized areas. Costs of the levees were estimated with standard Corps procedures, consistent with the accuracy necessary for a feasibility study; the annual equivalents are shown in Table 9-7.

b. Modification of functions. The levees proposed reduce damage in the basin by limiting out-of-bank flow onto protected area. This impact is represented with a modification to the stage-damage relationship. With a new Corps levee in place, the stage at which damage initially is incurred rises to an elevation equal to the elevation of the top of the levee. When the water-surface elevation exceeds the top-of-levee elevation, water flows onto the floodplain. Detailed analysis of overflow hydraulics will define the relationship between interior-area stage and stage in the channel. From this, appropriate damage in the interior or protected area can be determined. For Chester Creek, the interior-area and channel stage are assumed equal, so the damage incurred when the levee is overtopped is equal to that incurred without the levee. For example, with the 6.68-m levee in place, the without-project stage-damage relationship of Table 9-4 is modified to yield Table 9-8. Both relationships are plotted in Figure 9-6. If the stage in the protected or interior area would not reach the same stage as in the channel when the levee is overtopped, a relationship between interior and exterior (channel) stage can be developed and used in the analysis.

For the Chester Creek example, the stage-discharge function is not changed significantly by the levee. If the rating function did change, the modified rating would be used with the modified stage-damage relationship for each alternative.

c. Economic analysis. The economic efficiency of each levee plan is evaluated via sampling, using the

Table 9-7
Present Economic Benefits of Levee Alternatives

Plan	Annual With-project Residual Damage, in $1000	Annual Inundation Reduction Benefit, in $1000	Annual Cost, in $1000	Annual Net Benefit, in $1000
6.68-m levee	50.6	27.5	19.8	7.7
7.32-m levee	39.9	38.2	25.0	13.2
7.77-m levee	29.6	48.5	30.6	17.9
8.23-m levee	18.4	59.7	37.1	22.6

Table 9-8
Existing Conditions Stage-Damage Relationship with 6.68-m Levee

Stage, in m	Inundation damage, in $1000
3.35	0.0
4.27	0.0
4.57	0.0
5.18	0.0
5.49	0.0
6.10	0.0
6.68	0.0
6.71	2,150.6
8.23	5,132.8
8.53	5,654.2
9.14	6,416.5
9.45	6,592.3

modified stage-damage relationship appropriate for each alternative. The entire range of possible events is sampled, as is the range of uncertainty in the discharge-frequency, stage-discharge, and stage-damage relationships. (With new levees, geotechnical performance is assumed to be known with certainty. No uncertainty description is developed, and no sampling is conducted). The resulting expected annual damage estimates are shown in Table 9-7. The inundation-reduction benefit of each plan is shown; this is the difference in the with-project damage and the without-project damage ($78,100). The net benefit is computed as the cost less inundation-reduction benefit. Location and intensification benefits might increase this value.

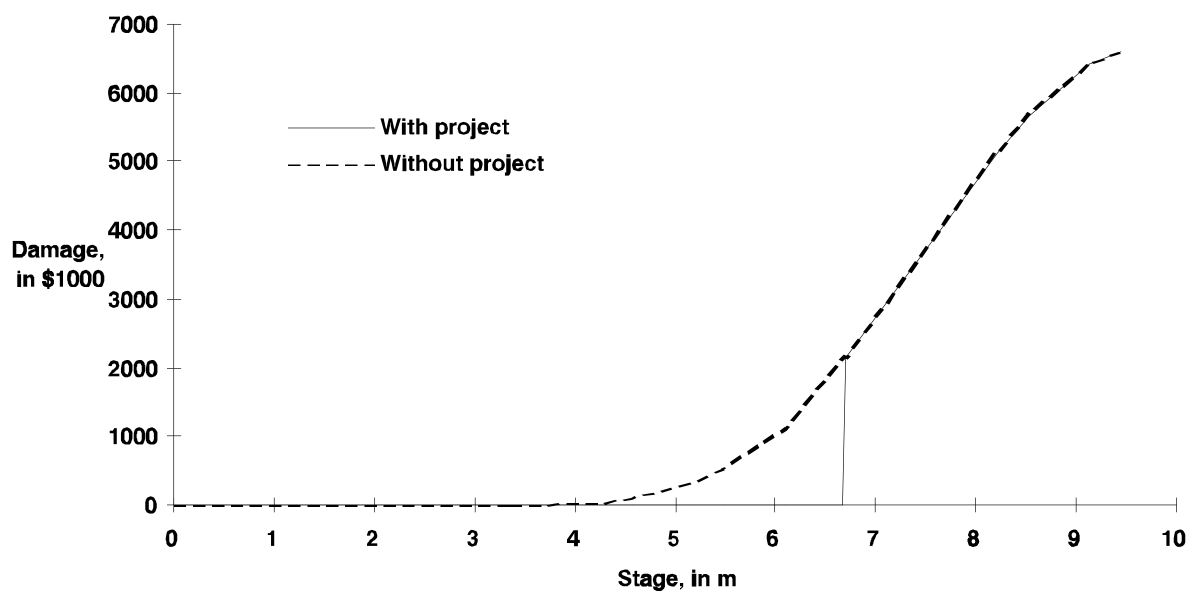

Figure 9-6. Present-condition stage-damage functions without and with 6.68-m levee

d. Engineering performance.

(1) Table 9-9 reports indices of engineering performance of the levee plans. For reference, the median annual exceedance probability that corresponds to the top-of-levee stage is determined by direct reference to the stage-discharge and discharge-frequency relationships shown in Table 9-3 and Table 9-2, respectively. The annual exceedance probability with uncertainty analysis values equals the annual exceedance probability with uncertainty included. These represent the protection provided, incorporating explicitly the uncertainty in predicting discharge associated with a specified probability and in predicting stage associated with discharge. In each case, the value is the probability with which the stage, with error included, exceeds the specified top-of-levee in the simulation for economic evaluation. For example, with the 6.68-m levee, the simulated water-surface elevation with errors included exceeded the top-of-levee elevation 61 times in 5,000 iterations. Therefore, the annual exceedance probability is 61/5,000 = 0.0122. This differs from the median exceedance probability in column 2 because of the interaction of errors in discharge and stage.

(2) The long-term risk shows the probability that each levee would be overtopped at least once during the 10, 25, or 50-year time period. These values are computed using the annual exceedance probability values. For the 8.23-m levee, the odds of exceedance are about 1-in-7, while for the 6.68-m levee, the odds approach 1-in-2.

(3) Table 9-10 shows the conditional non-exceedance probability of the levee plans for six benchmark events. The values shown are frequencies of *not* exceeding the levee capacity, given occurrence of the events shown. For example, for the 8.23-m levee, the conditional non-exceedance probability for the 0.02 exceedance probability event is 0.997. That means that should a 0.02 exceedance probability event occur, the probability is 0.997 that it would not exceed the capacity of the levee. This is estimated via simulation in which only 0.02 exceedance probability events are sampled. For each sample, error in discharge and stage is included.

(4) The probability with which the result does not exceed the top-of-levee elevation is determined. Here, with 5,000 iterations of the 0.02 exceedance probability event, the 8.23-m levee was not overtopped in 4,985, or 99.7 percent, of the iterations.

(5) Table 9-10 shows that the conditional non-exceedance probability is about 0.50 for events that yield stages equal to the proposed top-of-levee stages. For example, the median exceedance probability corresponding to 6.68 m is 0.01. However, the conditional non-exceedance probability of the 6.68-m levee plan for the 0.01-probability event is only 0.483. Similarly, the conditional non-exceedance probability of the 7.77-m levee, which has top of levee at stage corresponding to the 0.4-percent-chance event, has conditional non-exceedance probability equal to 0.489 for the 0.4-percent-chance event.

Table 9-9
Annual Exceedance Probability and Long-term Risk

Plan	Median Estimate of Annnual Exceedance Probability	Annual Exceedance Probability with Uncertainty Analysis	Long-term risk 10 yr	25 yr	50 yr
6.68-m levee	0.010	0.0122	0.12	0.26	0.46
7.32-m levee	0.007	0.0082	0.08	0.19	0.34
7.77-m levee	0.004	0.0056	0.05	0.13	0.25
8.23-m levee	0.002	0.0031	0.03	0.08	0.14

Table 9-10
Conditional Non-Exceedance Probability

Plan	Probability of Annual Event 0.02	0.01	0.004
6.68-m levee	0.882	0.483	0.066
7.32-m levee	0.970	0.750	0.240
7.77-m levee	0.990	0.896	0.489
8.23-m levee	0.997	0.975	0.763

9-8. Channel-Modification Plans

a. General. The channel-modification plan reduces damage in Chester Creek by making the channel “more efficient.” That is, the improved channel will carry greater discharge within its banks, without overflowing onto the surrounding floodplain. To achieve this, 730 m of the channel will be realigned, and the cross section will be reshaped to provide a 15-m bottom width and 43-m top width. The channel will be lined with riprap. The equivalent annual cost of this plan is $36,400.

b. Modification of functions.

(1) The proposed channel modifications will alter the stage-discharge relationship. The form of the modified relationship was determined with computer program HEC-2. To do this, the calibrated without-project model was altered to describe the modified channel, and the model was executed for a range of steady flows. From the computed water-surface elevations at the Chester Creek index point, the modified stage-discharge relationship shown in Table 9-11 was developed. Both this modified relationship and the existing-condition relationship are shown in Figure 9-7. (Only one channel plan is shown here. For completeness, a set of sizes and configurations should be evaluated).

Table 9-11
Modified Stage-Discharge Relationship

Stage, in m	Discharge, in m^3/s
0.76	56.6
1.71	113.3
2.47	169.9
3.20	226.6
3.78	283.2
4.72	396.5
5.67	509.8
6.40	623.0
7.07	736.3
7.65	849.6
8.23	962.9
8.60	1,076.2
9.08	1,189.4
9.20	1,246.1
9.60	1,302.7

(2) As was the case with the without-project stage-discharge relationship, the with-project rating function is not known with certainty because the model parameters and boundary conditions are not known with certainty. Sensitivity analyses with the HEC-2 model show a 0.9-m difference between the upper and lower bounds on the 0.01 exceedance probability water-surface elevation. As before, the stage-prediction errors are assumed to be normally distributed. If 95 percent of stages predicted for the 0.01 exceedance probability event should fall between the bounds, the standard deviation is 0.23 m. Note that for this modified condition, the geometry and *n* values are better known, as the shape and material are “engineered.” Thus the computed with-project stage-discharge relationship is more certain than the without-project relationship.

c. Economic analysis. To compute the benefit of the proposed channel plan, the entire range of possible events is sampled, along with the range of uncertainty in the discharge-frequency, stage-discharge, and stage-damage relationships. The expected annual damage is $41,200, and the inundation-reduction benefit is $36,900. The latter is the difference in the with-project damage and the without-project damage. The net benefit, computed as the cost ($25,000) less inundation-reduction benefit, is $11,900. In this case, inundation-reduction benefit exceeds cost, so the plan is feasible. Other benefits, such as location and intensification benefits, would affect the net benefit, and might alter this.

d. Engineering performance. For analysis of engineering performance, conditional non-exceedance probability of the 0.02-, 0.01-, and 0.004-exceedance probability events is determined. In order to define this conditional probability, a target stage of 4.58 m is selected, and the frequency of non- exceedance is computed. This stage was identified as the stage at which significant damage begins in the floodplain. The median probability associated with this stage is 0.027; this was determined by estimating first the discharge corresponding to 4.58 m (378.2 m^3/s) and then estimating the probability of exceeding that discharge. This does not account for errors in predicting discharge or stage. The annual exceedance probability, however, does. With 4,500 samples, the annual exceedance probability, the frequency with which stage exceeded 4.58 m, is 0.031. The long-term risk, in this case the probability that the 4.58-m target will be exceeded at least once in the 50-year project life, is 0.79. This value is quite large, but it does not indicate the consequence of capacity exceedance. In fact, with this channel modification, the impact of exceedance might be less than a meter near the channel, or it could be a very large flood with significant depths of flooding. The conditional probability for the 0.02-, 0.01-, and

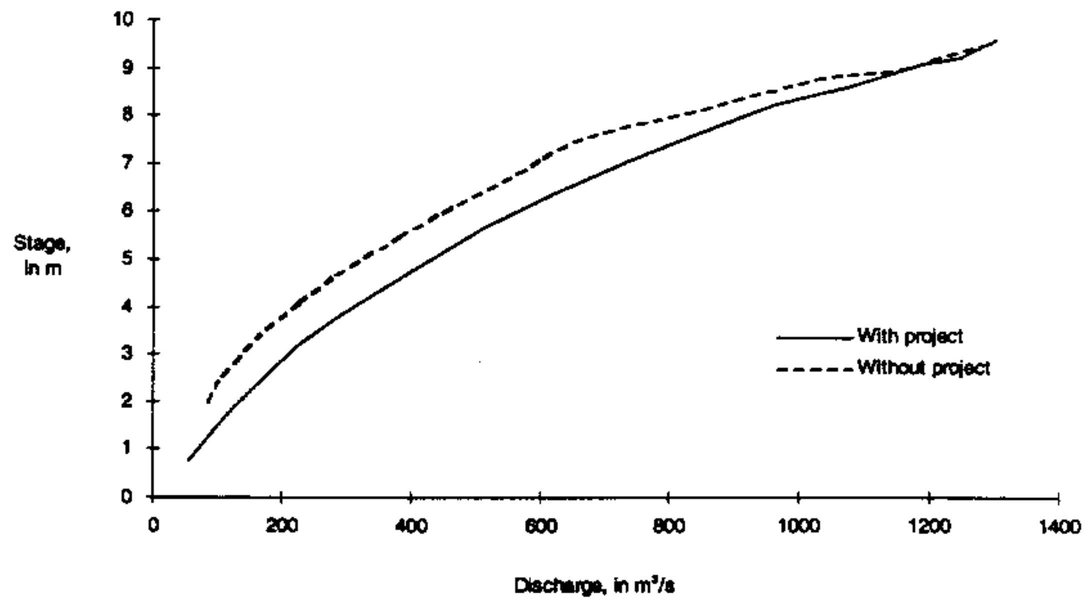

Figure 9-7. Stage-discharge functions without and with channel modification

0.004-exceedance probability events is 0.25, 0.02, and 0.00, respectively. These values indicate that with the channel modification, it is very likely that a 0.01 exceedance probability or greater flood will cause stage to exceed the 4.58-m target.

9-9. Detention Plan

a. General. The proposed detention basin is on the West Branch of Chester Creek. Runoff from 57.8 km^2 will be regulated by a 305-m-long structure, which impounds 5.55 million m^3 at full pool. However, to maintain the riverine recreation opportunities, the detention is designed to have no permanent storage: all flood waters will drain through an uncontrolled outlet after every event. The annual equivalent cost of this plan is $17,500. As with the levee plans, a variety of detention basin sizes and locations should be evaluated, but for illustration only, one is considered herein.

b. Modification of functions. The primary impact of storage is reduction of downstream discharge, and hence modification of the downstream discharge-frequency relationship. This reduction can be modeled for individual runoff events with routing models described in EM 1110-2-1417, and from this, the regulated frequency relationship can be defined. For Chester Creek, computer program HEC-1 was used for the routing. A set of historical and hypothetical events was routed through the stream system to Dutton Mill. From the without-project median discharge-frequency relationship there, the exceedance probability of each unregulated peak was found. Then the same events were routed through the system with the detention included in the model. Each regulated peak was assigned the same probability as the corresponding unregulated peak. Selected quantiles of the resulting regulated discharge-frequency relationship are shown in Table 9-12. Quantiles are approximately the same as those of the without-project relationship (Table 9-2) for frequent, smaller events. For larger events, the detention basin reduces the peak.

Uncertainty in the Chester Creek regulated discharge-frequency was determined with the LIMIT computer program. This program uses order statistics to establish the error in predicting the regulated quantile. For this application of LIMIT, the equivalent length of record was 65 years, and log transforms of the data are used.

c. Economic analysis. The expected annual damage with the proposed detention plan is $44,100. To determine this, the entire range of possible events is sampled, as are the distributions of error in discharge, stage, and damage. Damage reduction possible with the

Table 9-12
Chester Creek Regulated Discharge-Frequency Relationship

Probability of Exceedance	Discharge, in m^3/s
0.002	821.3
0.005	560.7
0.01	424.8
0.02	331.3
0.05	243.6
0.10	192.6
0.20	153.6
0.50	87.0
0.80	50.9
0.90	39.4
0.95	32.3
0.99	22.9

detention plan then is $34,000. With the total annual cost of the plan equal to $35,800, the resulting annualized net benefit is -$1,800, so the plan is not feasible. However, other benefits could affect the total, and thus may make the plan feasible.

d. Engineering performance. To define indices that describe the performance of the detention plan, the target stage is set at 4.58 m. The median exceedance probability of this stage is 0.033, and the annual exceedance probability, accounting for uncertainty, is 0.035. The probability of one or more exceedances in a 50-year project life is 0.83. The conditional non-exceedance probability of the plan for the 0.02-, 0.01-, and 0.004-exceedance probability events are 0.21, 0.04, and 0.003, respectively.

9-10. Mixed-Measure Plan

a. Modification of functions. The final plan proposed for Chester Creek is a mixed-measure plan that includes both the proposed channel straightening and enlarging and the 5.55-million-m^3 detention. Consequently, both the discharge-frequency relationship and the stage-discharge relationship will be modified. The annual equivalent cost of this plan is $45,600. This is less than the sum of the cost of the individual plans, due to some economy of scale achieved in mobilization and demobilization of construction equipment and significant reduction in cost of haul of fill material.

b. Economic analysis. Expected annual damage with the mixed-measure plan is $24,500, so the annual damage reduction is $53,600. This is less than the sum of the inundation-reduction benefit of the individual measures. Much of the damage reduced is damage incurred by events less than or equal to the 1-percent-chance event. Either the channel modification or the detention will eliminate most of the damage, and the second measure can only reduce the remaining damage. That remaining damage is due to rarer events, and so contributes little to the average annual damage. The net benefit of the plan is $8,000 ($53,600 - $45,600).

c. Engineering performance. For comparison, a 4.58-m target stage is used. The annual exceedance probability is 0.016, while the estimated median probability is 0.014. The difference is due to uncertainty in estimating discharge corresponding to the stage and probability corresponding to the discharge. The risk of exceeding the target stage at least once during the 50-year project life is 0.55. The conditional non-exceedance probability for the 0.02-, 0.01-, and 0.004-exceedance probability events are 0.74, 031, and 0.04, respectively.

9-11. Comparison of Plans

a. Table 9-13 summarizes the without-project condition and the economic accomplishments of each of the proposed plans. All plans proposed significantly reduce the $78,100 expected annual damage. The 6.68-m levee, which provides the least reduction, still eliminates about one-third of the average damage. The 8.23-m levee and the mixed measure plan eliminate about two-thirds of the average damage. The detention basin plan eliminates about half the average damage, but the cost of that plan exceeds the damage reduced. Unless the associated location and intensification benefits exceed $1,800/yr, the detention plan should be eliminated from further consideration. The net benefit of the 8.23-m levee exceeds all others, so from a narrow economic point of view, it would be recommended. The next-best plan economically is the 7.77-m levee, followed in order by the 7.32-m levee, the channel-modification plan, the mixed measure plan, and the 6.68-m levee.

b. Table 9-14 summarizes engineering performance indices for the proposed plans. With the detention basin plan, the target stage downstream will be exceeded, on the average, about 38 times in 1,000 years. However, this exceedance likely can be forecast with some certainty, so will not be sudden and catastrophic. Thus, the consequences may be acceptable. The same is true of the channel modification: the capacity is exceeded frequently, but this likely will not imperil the public due to sudden failure. On the other hand, the consequences of

Table 9-13
Present Economic Benefits of Alternatives

Plan	Annual With-Project Residual Damage, $1000's	Annual Inundation Reduction Benefit, $1000's	Annual Cost, $1000's	Annual Net Benefit, $1000's
Without project	78.1	0.0	0.0	0.0
6.68-m levee	50.6	27.5	19.8	7.7
7.32-m levee	39.9	38.2	25.0	13.2
7.77-m levee	29.6	48.5	30.6	17.9
8.23-m levee	18.4	59.7	37.1	22.6
Channel modification	41.2	36.9	25.0	11.9
Detention basin	44.1	34.0	35.8	-1.8
Mixed measure	24.5	53.6	45.6	8.0

Table 9-14
Annual Exceedance Probability and Long-term Risk

Plan	Median Estimate of Annual Exceedance Probability	Annual Exceedance Probability with Uncertainty Analysis	Long-term Risk		
			10 yr	25 yr	50 yr
6.68-m levee	0.010	0.0122	0.12	0.26	0.46
7.32-m levee	0.007	0.0082	0.08	0.19	0.34
7.77-m levee	0.004	0.0056	0.05	0.13	0.25
8.23-m levee	0.002	0.0031	0.03	0.08	0.14
Channel modification	0.027	0.031	0.27	0.55	0.79
Detention basin	0.033	0.038	0.32	0.62	0.86
Mixed measure	0.014	0.016	0.15	0.33	0.55

exceeding the top-of-levee stages are significant. Fortunately, according to the values shown in column 3, the probability of exceeding this target stage is relatively low for all proposed configurations. The 6.68-m levee will be overtopped on the average about 12 times in 1,000 years, while the 8.23-m levee will be overtopped on the average only three times in the same period.

c. Table 9-15 shows that the conditional non-exceedance probability for the levee plans are significantly greater that those of the other plans. This can be seen clearly if the conditional non-exceedance probability values are plotted, as in Figure 9-8. The conditional non-exceedance probability for the channel modification and detention plans are only about 0.20-0.25 for the 0.02 exceedance probability event. That is, if a 0.02 exceedance probability event occurs (and the probability is 0.63 that it will at least once in the 50-year lifetime), the probability of some flooding is about 0.75-0.80 with either of these. The conditional non-exceedance probability improves when the detention and channel modification are combined. In that case, the probability of target exceedance is reduced to about 0.30 for the 0.02 exceedance probability event. The levee plans, though, appear to be far superior in performance. The 8.23-m levee is almost sure to contain the 0.02 exceedance probability event, and the probability is about 0.75 that it will contain the 0.004-exceedance probability event. However, this performance index is a bit misleading: with the higher levees, the target has shifted from 4.58 m to 8.23 m. Nevertheless, the levee plans provide more reliable damage reduction. If the 8.23-m levee plan is acceptable to local sponsors, if the consequences of overtopping can be managed to within reasonable limits, and if it does not adversely impact the environment, it would likely be recommended.

Table 9-15
Conditional Non-Exceedance Probability

	Probability of Annual Event		
Plan	**0.02**	**0.01**	**0.004**
6.68-m levee	0.882	0.483	0.066
7.32-m levee	0.970	0.750	0.240
7.77-m levee	0.990	0.896	0.489
8.23-m levee	0.997	0.975	0.763
Channel modification	0.248	0.019	0.000
Detention basin	0.205	0.040	0.003
Mixed measure	0.738	0.312	0.038

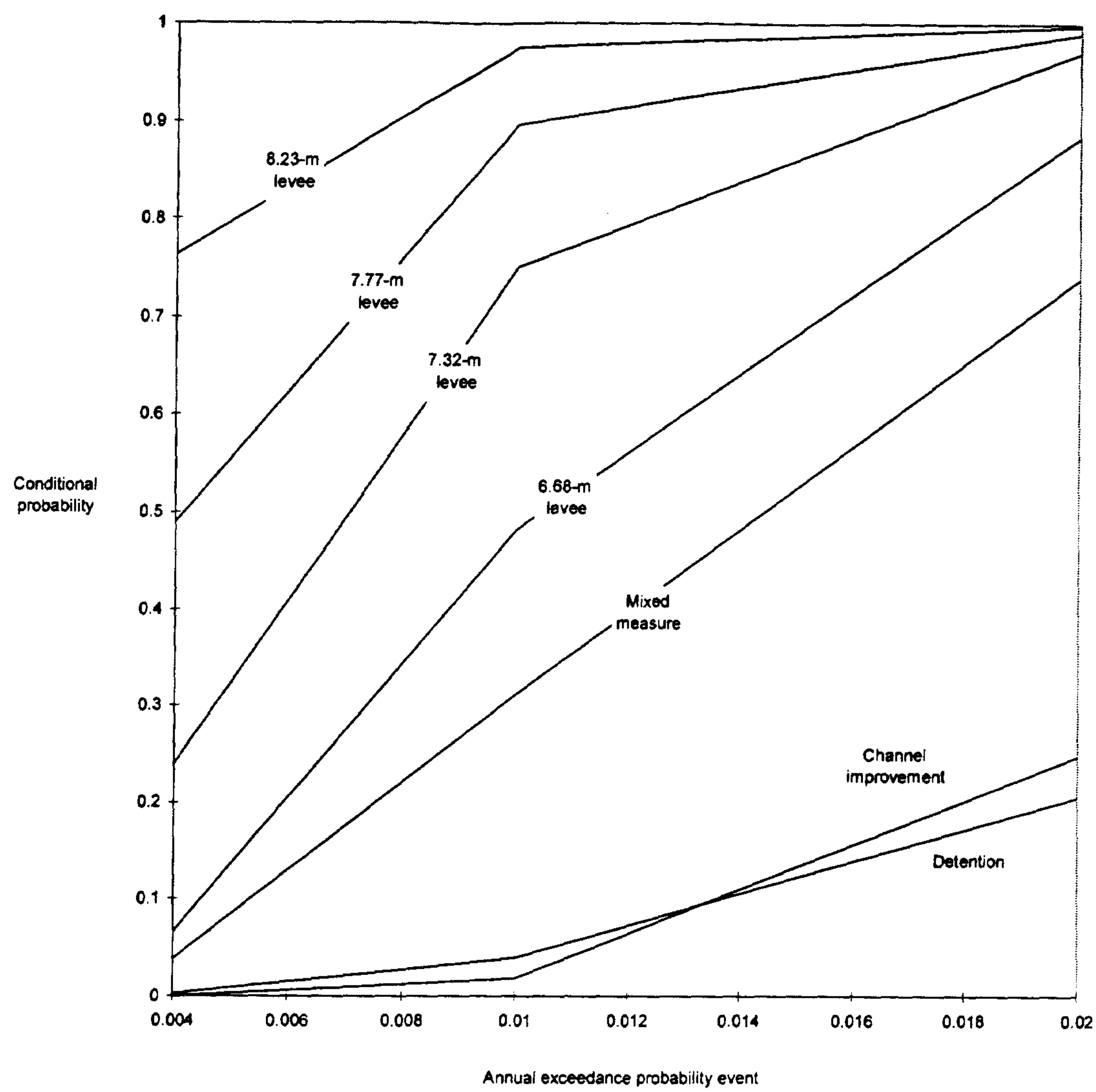

Figure 9-8. Conditional exceedance probability of proposed plans